AN-208
Application Note

A UNIQUE ULTRA-HIGH-SPEED SWITCHING-TIME TEST DEVICE

Prepared by
Jack Schroeder
Applications Engineering

Ultra-high-speed test fixture allows accurate measurement of switching times for a variety of transistors.

MOTOROLA *Semiconductor Products Inc.*

INTRODUCTION

The development of faster and faster switching transistors has created such a severe measurement problem that it has become extremely difficult to accurately measure device switching time with commercially available test equipment.

For accurate testing of high-speed transistors, a step generator must have fast rise and fall time (less than one nanosecond), an adequate pulse width (greater than 10 microseconds) and a low "on" duty cycle to reduce power dissipation in the transistor under test.

Since no single pulse generator is commercially available, the Motorola Semiconductor Products Applications Engineering Department developed a simple, inexpensive and versatile test circuit for internal use. This circuit has been well proven in both laboratory and production use.

The conventional method of measuring transistor switching characteristics uses a pulse generator to drive the transistor to the "on" state. Using the leading edge of the input pulse to mark time, the delay and rise time of the transistor can be measured. If the trailing edge of the input pulse is fast enough, and the pulse width is long enough to insure maximum stored charge in the transistor, the storage and fall times of the transistor also can be measured accurately.

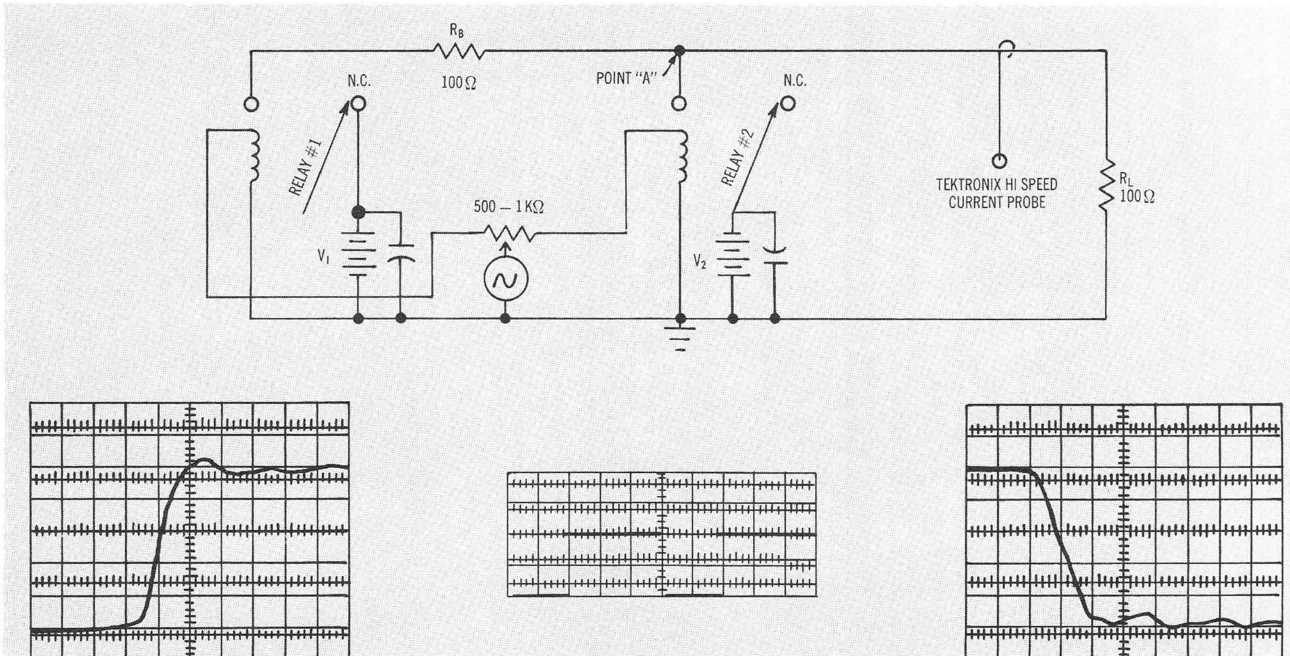
Because many fast rise time generators have long fall times or are limited in pulse width, a second approach must be used to measure turn-off time. This has the transistor biased "on" and the fast rise input pulse is used to turn the transistor off. Thus, the storage and fall times can be accurately measured. The storage time of many devices having fast rise and fall times is long, however, and a wide pulse must be used to turn the transistor off completely. In addition, the "on" time duty cycle of the transistor is extremely long which causes the transistor junction temperature to increase well above ambient - giving erroneous storage and fall time measurements.

With the increasingly short switching time of new transistors, it is increasingly difficult to find wide-pulse width generators fast enough for use in measuring accurate switching times. For example, one widely used pulse generator has an extremely fast rise time, but long pulse widths are difficult to achieve because the charge cable, which controls the pulse length, becomes prohibitively long. For many transistors, pulse widths of several microseconds are needed to allow the transistor excess charge to reach an equilibrium state. It would take 500 feet of charge cable to produce a 1.0 microsecond pulse width with this generator. In addition, this type of pulse generator shows degradation of the falling edge of the pulse when long cable lengths are used.

THE TEST CIRCUIT

The Motorola switching time test circuit uses two mercury-wetted contact relays to satisfy all of the requirements for testing high-speed transistors. The pulse forming circuit is shown in Figure 1.

The "on" pulse is generated by relay #1 using the make-before-break characteristics of mercury wetted



a. CURRENT WAVE SHAPE THROUGH R_L RISE TIME 20 MA/CM 1NS/CM SWEEP TEKTRONIX 567 SCOPE

b. VOLTAGE WAVE SHAPE POINT "A" CENTER = GND 5 V/CM 1MS/CM SWEEP TEKTRONIX 585 SCOPE

c. CURRENT WAVE SHAPE THROUGH R_L FALL TIME 40 MA/CM 1NS/CM SWEEP TEKTRONIX 567 SCOPE

FIG. 1 — PULSE FORMING CIRCUIT WITH VOLTAGE AND CURRENT WAVE SHAPES

relays. (The relay contacts are temporarily bridged by a meniscus of mercury.) During the "on" pulse duration the second relay #2 closes producing a pulse of the opposite polarity. The rise and fall times of these pulses have been measured in the sub-nanosecond region.

The turn-on pulse width is usually between 25 to 100 microseconds. With a 100 microsecond pulse width operating at 200 cycles per second, the "on" time duty cycle is only 2 percent.

Figure 1a shows the rise time of the current step through the load resistor R_L. A 100 mA current step with turn on time (10-90%) of 1.1 nS is shown. Figure 1c shows the fall time of the 100 mA current step (10-90%) which is 1.2 nS. Figure 1b shows two cycles of the voltage waveform developed at point "A". The top line is the turn-on voltage level when relay #1 is on. The bottom line is the voltage level when relay #2 is on. The center line is the ground reference when both relays are off.

The relays are close relays type HGSM1011.

The relay coils can be driven with either an audio or pulse generator. The sequencing of the relays depends on the drive voltage and frequency applied to the coils. A pot is used to help sync the two relays. The design is capable of driving currents of 1 microamp to 1 amp with voltage amplitudes of millivolts to approximately 40 volts.

A practical switching time test fixture for NPN devices is shown in Figure 2, (for PNP devices all power supply voltages and clamp diode polarities are reversed).

Carbon resistors and short leads are used throughout to keep the inductance down. Since the end-to-end capacitance of the carbon resistors acts to speed transistor switching times, R_K, R_S and R_T should be ground-planed to reduce this feedthrough effect. The ground plane for these resistors should be as close as practical to the body of the resistors. The transistor socket is also ground-planed between base and collector to isolate the input from the output, thus reducing feedthrough and Miller effect.

For many switching time measurements, the turn-on current (I_B1) and the turn-off current (I_{B2}) required are equal. Unfortunately, the off-bias (V_{OB}) normally is not high enough to simulate a good current source while supplying the required turn-off current (I_{B2}). In addition, the transistor BV_{EBO} is usually less than the drive voltage required to produce a good current source (typically 10 volts or higher).

Diode D_1 is used to clamp the transistor base to prevent breakdown of the emitter base junction during the time after the transistor has turned off and while the off voltage pulse is still present. Diode capacitance should be small compared to the sum of C_{ib} and C_{ob} of the transistor under test. In any case the diode should not be used when delay time measurements are being made.

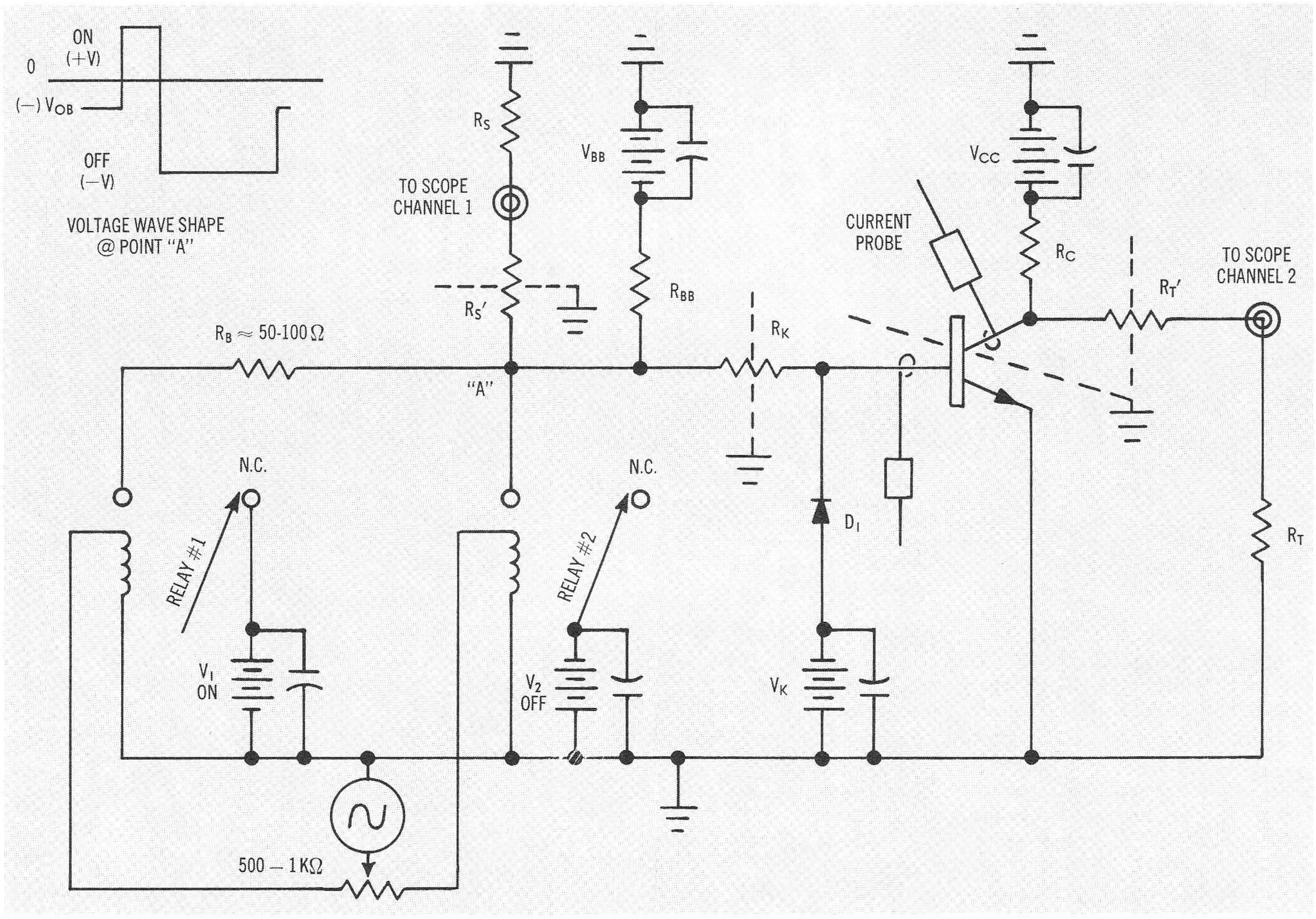


FIG. 2 — PRACTICAL SWITCHING TEST FIXTURE

Any hold-off supply voltage can be used with the clamp as long as the supply voltage plus the forward drop of the diode is less than the breakdown of the emitter base junction (BV_{EBO}) of the device being tested. A clamp diode directly to ground can be used; however, if large base currents are being run, the power dissipation in R_K during the off-time is high and use of a bias voltage will reduce dissipation.

In some cases where the r_b' of the transistor is large, the base voltage can reach the clamp level during turn-off before the collector current has completely turned off. This condition has been observed with devices operating at high current levels with small values of R_K. If this condition occurs, the clamp supply voltage should be set as close as possible to the BV_{EBO} of the transistor being tested. The base voltage should be monitored to insure that the transistor is "off" completely before the clamp turns on, otherwise the clamp will rob turn-off current from the transistor and the collector voltage fall time will exhibit a long tail. This fall time will, of course, be erroneous. The r_b' situation can be improved by increasing the drive voltage and increasing R_K proportionally to improve the current source. In some cases where r_b' is high and the BV_{EBO} is low, accurate fall time measurements cannot be made due to the inability of achieving a good current source.

V_{BB} and R_{BB} are used if an off bias, V_{OB}, is needed for the turn on delay time measurement. This bias arrangement effectively shifts the level of the basic waveshape shown in Figure 1.

All power supplies must be double or triple bypassed. A large electrolytic capacitor of 10 to 50 μf is needed to prevent low frequency oscillations. An 0.1 μf ceramic disc capacitor is used to prevent high frequency oscillations and in some cases, a mica capacitor of 50 pf to 500 pf is necessary to prevent very high frequency oscillations. The amount of bypassing necessary depends upon how much current is being switched, the rate of switching and the quality of the power supplies being used. All lead lengths should be kept to a minimum to reduce the lead inductance.

The chassis can be made of beryllium copper or brass. These materials are easy to solder and also provide an excellent ground for the entire circuit. RF connectors (BNC type) are used for the input and output monitor points.

A four-lead socket, split to provide a ground plane between the base and collector leads to reduce capacitance from the input to the output, is used. The test device should be mounted flush with the socket to prevent the inductance of the transistor leads from affecting the measurements.

A voltage divider is used to monitor the input voltage to prevent the probe or scope capacity from distributing the input pulse waveshape. In addition, the divider provides a pick off for triggering the scope. A voltage divider is also shown on the output to keep the probe or scope capacity from adding capacitance at the collector which could affect the switching times. The effect of collector to ground capacitance is particularly disturbing to fall time measurements.

Voltage probes, current probes or coaxial cables can be used to couple the waveforms to the scope. The input and output waveforms should be read with the same type of probe, however, to avoid the time delay between the voltage probe and the current probe. Switching times can, of course, be read using a combination of these probes, but the delay time between the two types of probes must be known for accurate switching time measurements. If cables are used, they should be terminated with their characteristic impedance at the scope input and should be of the same length and type to avoid time delay problems.

A voltage divider should be used with voltage probes due to the time constant of R_C (collector resistor) and C_P (probe capacity) which in many cases is an appreciable portion of the switching time to be measured. The R_C C_P charge time comes into effect most markedly when measuring the fall time of a transistor.

An example of a typical circuit without the voltage divider is given in Figure 3.

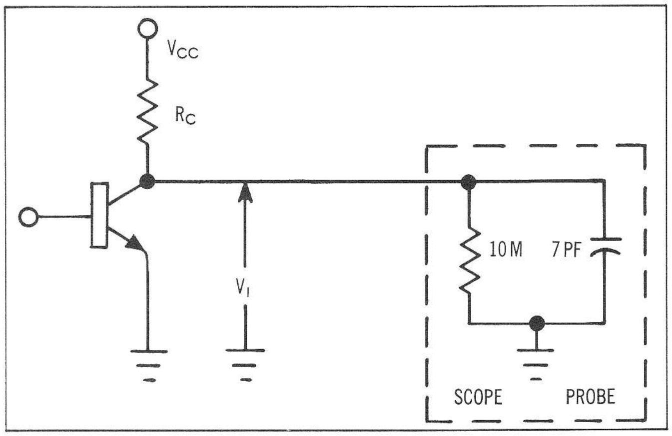


FIGURE 3 — OUTPUT CIRCUIT WITH SCOPE VOLTAGE PROBE

For V_{CC} = 10 V and R_C = 1 KΩ, the resulting I_C is 10 mA neglecting $V_{CE(sat)}$. The collector voltage swing V_1 is 10 V.

When the transistor is turned off, the 10 to 90% charge time of the probe is

$$t \cong 2.3\ R_C\ C_P \tag{1}$$

which for the example of Figure 3 may be solved to find

$$t \cong 2.3\ (1\ K)\ (7\ pf) = 16.1\ nS.$$

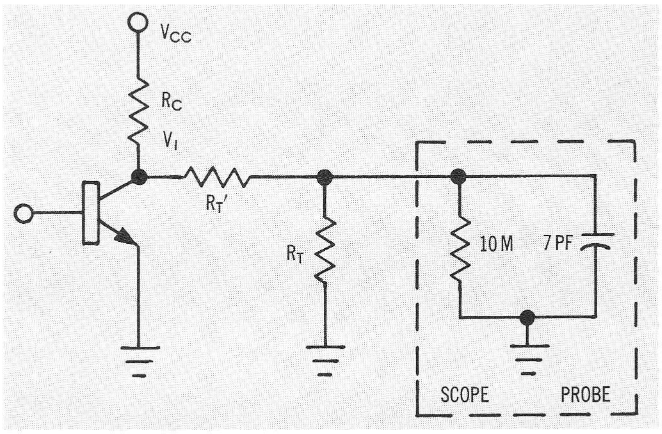


FIGURE 4 — OUTPUT CIRCUIT WITH VOLTAGE DIVIDER AND SCOPE VOLTAGE PROBE

For a high speed silicon switch, the probe charge time could be an appreciable amount of the switching time to be measured which would give an erroneous switching time measurement. Figure 4 shows the same circuit with a voltage divider.

With R_T = 50 ohms and a 50:1 voltage divider such that R_T = 2.4 K ohm, the voltage across R_T will be 200 mV. The charge time of the voltage probe is now negligible since:

$$t \cong 2.3\ (50)\ (7\ pf) = 0.8\ nS.$$

The collector current (I_C) and collector voltage swing (V_1) must still be 10 mA and 10 volts. I_C and V_1 are related to the circuit components by the following equations:

$$I_C = \frac{V_{CC}}{R_C} \quad (2)$$

$$V_1 = \frac{V_{CC}\ (R_T + R'_T)}{R_C + R_T + R'_T} \quad (3)$$

Solving Equation 3 for R_C and inserting the example conditions

$$R_C = \frac{V_1}{I_C - V_1/R_T + R'_T} = 1.69\ K\ ohms$$

V_{CC} may now be found from Equation 2 as

$$V_{CC} = R_C\ I_C = (1.69\ K)\ (10\ mA) = 16.9\ volts$$

COUPLING DIRECTLY TO THE SCOPE

For adequate display, a typical oscilloscope with preamp requires a minimum input of 20 mV. With a 10:1 voltage probe reading across R'_T as in Figure 4, the scope does have 20 mV available for display. However, in many cases there isn't enough voltage available at the voltage divider to permit the use of a voltage probe and coaxial cables must be used to couple the signal directly to the scope input in order to gain sensitivity. The cable should be terminated at the preamp with its characteristic impedance. Figure 5 shows 50 ohm coaxial cable and the divider of Figure 4.

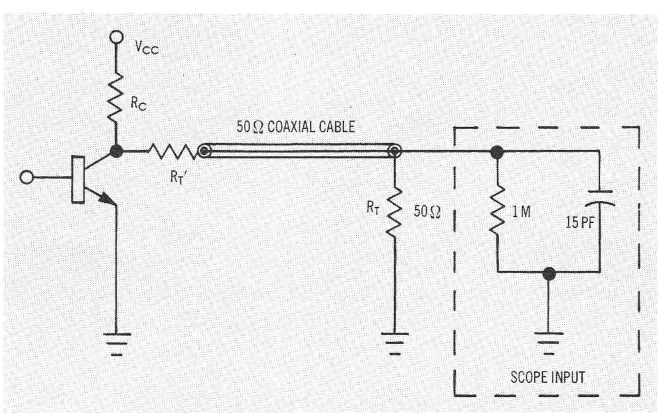


FIGURE 5 — OUTPUT CIRCUIT WITH VOLTAGE DIVIDER AND SCOPE INPUT USING 505L COAXIAL CABLE

The charge time of the scope is now

$$t \cong 2.3\ (C_{in})\ (R_T)$$

$$t \cong 2.3\ (15\ pf)\ (50) = 1.7\ nS$$

The charge time has increased, due to the higher capacitance of the preamp as compared to the capacitance of the 10:1 voltage probe, but normally 1.7 nS is an acceptable charge time. The available voltage at the scope is now 200 mV compared to 20 mV using the 10:1 voltage probe.

This technique provides an adequate voltage signal to accurately measure the switching times; however, several precautions must be taken.

1) The coaxial cables must be terminated with their characteristic impedance.

2) The input and output cables should be the same length to avoid the delay that occurs between the two cables of different lengths.

3) If the trigger for the scope is taken from the input voltage divider, this extra length of cable must be taken into account. Figure 6 shows a typical hook-up.

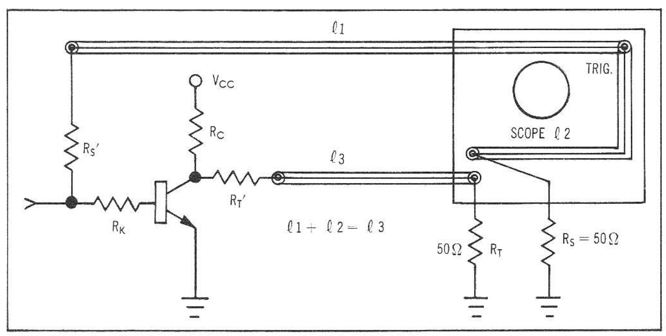


FIGURE 6 — INPUT MONITOR AND OUTPUT CIRCUIT WITH VOLTAGE DIVIDER AND 50Ω COAXIAL CABLES TO SCOPE INPUTS

Several commercially available oscilliscope current probes provide adequate sensitivity for measuring switching times. Care should be taken, however, to insert the current probes on the base side of the clamp diode and on the collector lead as shown in Figure 2. The delay and rise time measurements can be made first by triggering the scope on the positive going slope of the input voltage; i.e., from the zero or V_{OB} level up to the on (+) voltage. By triggering on the negative slope of the input voltage; i.e., from the time level (+) voltage to the off time level (-), voltage the storage and fall time measurements can be made. No further adjustments have to be made once the circuit is set up for the proper currents.

SUMMARY

The minimum requirements for a pulse generator used to measure the switching characteristics of high speed switching transistors are 1) rise and fall times less than 1 nS, 2) on-time pulse width greater than 10 μs and 3) on-time duty cycle less than 5 per cent. This report described in detail the construction of a reliable and economical switching test fixture that meets these requirements. The test fixture has a low duty cycle (2%) on time and is capable of accurately measuring all switching parameters from microamps to about one amp with a minimum of set up time.

MOTOROLA Semiconductor Products Inc.

BOX 955 • PHOENIX, ARIZONA 85001 • A SUBSIDIARY OF MOTOROLA INC.

987-1 PRINTED IN USA 3-66 IMPERIAL LITHO 8845